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NuTeV

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NuTeV**

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DETERMINATION OF $\sin^2 \theta_W$ FROM NEUTRINO-NUCLEON SCATTERING AT NuTeV

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Abstract

We report the determination of $\sin^2 \theta_W$ in $\nu - N$ deep inelastic scattering from the NuTeV experiment. Using separate neutrino and anti-neutrino beams, NuTeV is able to extract $\sin^2 \theta_W$ with low systematic errors from the Paschos-Wolfenstein variable R^- , a ratio of differences of neutrino and anti-neutrino neutral-current and charged-current cross-sections. NuTeV measures $\sin^2 \theta_W^{(\text{on-shell})} = 0.2253 \pm 0.0019(\text{stat}) \pm 0.0010(\text{syst})$, which implies $M_W = 80.26 \pm 0.11$ GeV.

1 Introduction

In the past, neutrino scattering experiments have played a key role in establishing the validity of the electroweak Standard Model. Today, even with the large samples of on-shell W and Z bosons at e^+e^- and $p\bar{p}$ colliders, precision measurements in neutrino-nucleon scattering still play an important role. The measurement reported herein is competitive in precision with direct probes of weak boson parameters and tests the validity of the electroweak theory by determining $\sin^2 \theta_W$ in a different process and at small q^2 . In this respect, if neutrino scattering observed deviations from expectations based on direct measurements from W and Z bosons, this would be an exciting hint of new physics entering in tree-level processes or in radiative corrections. In particular, neutrino scattering would be sensitive to non-Standard Model effects ranging from leptoquark exchange to neutrino oscillations[1, 2].

Experimental quantities sensitive to electroweak physics that are most precisely measured in neutrino scattering are the ratios of charged-current (W exchange) to neutral-current (Z exchange) scattering cross-sections from quarks in heavy nuclei. The ratio of these cross-sections for either neutrino or anti-neutrino scattering from isoscalar targets of u and d quarks can be written as[3]

$$R^{\nu(\bar{\nu})} \equiv \frac{\sigma(\bar{\nu}_{\mu} N \rightarrow \mu^+ X)}{\sigma(\nu_{\mu} N \rightarrow \mu^- X)} = (g_L^2 + \frac{g_R^2}{r}), \quad (1)$$

where

$$r \equiv \frac{\sigma(\bar{\nu}_{\mu} N \rightarrow \mu^+ X)}{\sigma(\nu_{\mu} N \rightarrow \mu^- X)} \sim \frac{1}{2}, \quad (2)$$

and $g_{L,R}^2 = u_{L,R}^2 + d_{L,R}^2$, the isoscalar sums of the squared left or right-handed quark couplings to the Z . At tree level in the Standard Model, $q_L = I_{\text{weak}}^{(3)} - Q_{\text{EM}} \sin^2 \theta_W$ and $q_R = -Q_{\text{EM}} \sin^2 \theta_W$; therefore, R^{ν} is particularly sensitive to $\sin^2 \theta_W$.

In a real target, there are corrections to Eqn. 1 resulting from the presence of heavy quarks in the sea, the production of heavy quarks in the target, non leading-order quark-parton model terms in the cross-section, electromagnetic radiative corrections

and any isovector component of the light quarks in the target. In particular, in the case where a charm-quark is produced from scattering off of low- x sea quarks, the uncertainties resulting from the effective mass suppression of the heavy final-state charm quark are large. The uncertainty in this suppression ultimately limited the precision of previous νN scattering experiments which measured electroweak parameters[4, 5, 6].

To eliminate the effect of uncertainties resulting from scattering from sea quarks, one can instead form a quantity suggested by Paschos and Wolfenstein[7],

$$R^- \equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} \quad (3)$$

$$= \frac{R^\nu - r R^{\bar{\nu}}}{1 - r} = (g_L^2 - g_R^2). \quad (4)$$

Since $\sigma^{\nu q} = \sigma^{\bar{\nu} \bar{q}}$ and $\sigma^{\bar{\nu} q} = \sigma^{\nu \bar{q}}$, the effect of scattering from sea quarks, which is symmetric under $q \leftrightarrow \bar{q}$, cancels in the difference of neutrino and anti-neutrino cross-sections. The remaining contribution from d_V yields a factor of roughly five smaller error from this process. R^- is a more difficult quantity to measure than R^ν , primarily because neutral current neutrino and anti-neutrino scattering have identical observed final states and can only be separated by *a priori* knowledge of the initial state neutrino.

2 The NuTeV Experiment and Neutrino Beam

The NuTeV detector consists of an 18 m long, 690 ton target calorimeter with a mean density of 4.2 g/cm³, followed by an iron toroid spectrometer. The target calorimeter consists of 168 iron plates, 3m \times 3m \times 5.1cm each. The active elements are liquid scintillation counters spaced every two plates and drift chambers spaced every four plates. There are a total of 84 scintillation counters and 42 drift chambers in the target. The toroid spectrometer is not directly used in this analysis. NuTeV used a continuous test beam of hadrons, muons and electrons to calibrate the calorimeter and toroid response. The testbeam illuminated the front of the calorimeter in-

between extractions of the fast-spill neutrino beam (≈ 4 msec) and the testbeam was pointed to study transverse variations in detector response.

In this detector $\nu_\mu/\bar{\nu}_\mu$ charged-current events are identified by the presence of an energetic muon in the final state which travels a long distance in the target calorimeter. Quantitatively, a length is measured for each event based on the number of neighboring scintillation counters above a low threshold. Charged-current candidates are those events with a length of greater than 20 counters (2.1 m of steel-equivalent), and all other events are neutral-current candidates.

NuTeV's target calorimeter sits in the Sign-Selected Quadrupole Train (SSQT) neutrino beam at the FNAL TeVatron. The observed neutrinos result from decays of pions and kaons produced from the interactions of 800 GeV protons in a production target. Immediately downstream of the target, a dipole magnet with $\int Bdl = 5.2$ T-m bends pions and kaons of one charge in the direction of the NuTeV detector, while oppositely charged and neutral mesons are stopped in dumps. Focusing magnets then direct the sign-selected mesons into a 0.5 km decay region which ends 0.9 km upstream of the NuTeV detector. The resulting beam is either almost purely neutrino or anti-neutrino, depending of the selected sign of mesons. Anti-particle backgrounds are observed at a level of less than 1–2 parts in 10³. The beam is almost entirely muon neutrinos, with electron neutrinos creating 1.3% and 1.1% of the observed interactions from the neutrino and anti-neutrino beams, respectively.

Because charged-current electron neutrino interactions usually lack an energetic muon in the final state, they are almost always identified as neutral-current interactions in the NuTeV detector. Therefore, the electron neutrino content of the beam must be very precisely known. Most (93% in the neutrino beam and 70% in the anti-neutrino beam) observed $\nu_e/\bar{\nu}_e$ s result from K_{e3}^\pm decays. The remainder are products of prompt decays of charmed particles or neutral kaons, or decays of secondary muons. Prediction of the former component comes from a beam Monte Carlo, tuned to reproduce the observed $\nu_\mu/\bar{\nu}_\mu$ flux (Figure 1). Because of the precise alignment of the magnetic optics in the SSQT (checked by observing deflections of the primary proton beam in a special

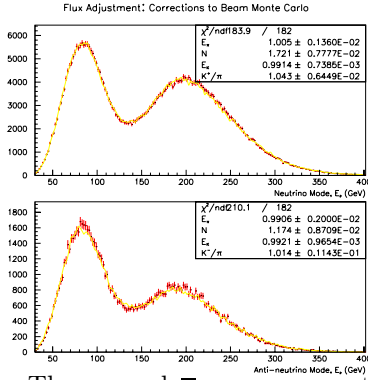


Figure 1: The ν_μ and $\bar{\nu}_\mu$ energy spectra from the data and the tuned beam Monte Carlo.

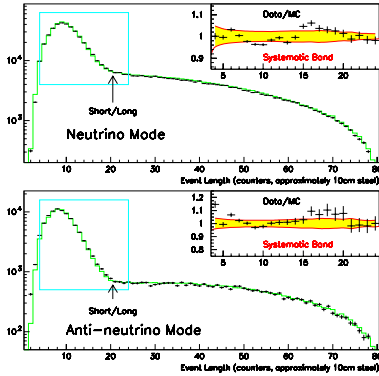


Figure 2: Length distributions in the data from the neutrino and anti-neutrino beams. Neutral-current/charged-current separation is made at a length of 20 counters, approximately 2.1 m of steel.

low-energy Tevatron run), this procedure results in a fractional uncertainty on the prediction of $\nu_e/\bar{\nu}_e$ from K_{e3}^\pm of $\approx 1.5\%$, dominated by the K_{e3}^\pm branching ratio uncertainty. Small detector calibration uncertainties, 0.5% on the calorimeter and muon toroid energy scale, affect the measured $\nu_\mu/\bar{\nu}_\mu$ flux and also contribute substantial uncertainties to both the muon and electron neutrino fluxes. Sources of $\nu_e/\bar{\nu}_e$ other than K^\pm decay have larger uncertainties, at the 10–20% level, because of the lack of a direct constraint

from the data.

3 Extraction of $\sin^2 \theta_W$

Events selected for this analysis are required to deposit at least 20 GeV in the target calorimeter to ensure efficient triggering and vertex identification. The location of the neutrino interaction must be within the central $2/3^{\text{rds}}$ of the calorimeter’s transverse dimensions, at least 0.4 m of steel-equivalent from the upstream end of the calorimeter, and at least 2.4 m from the downstream end. The first requirement reduces the misidentification of $\nu_\mu/\bar{\nu}_\mu$ events with muons exiting the side of the calorimeter; the second reduces non-neutrino backgrounds, and the third ensures sufficient calorimeter downstream of the interaction to measure the event length. Small backgrounds from cosmic-ray and muon induced events are subtracted from the sample. After all cuts, 1.3 million and 0.30 million events are observed in the neutrino and anti-neutrino beam, respectively. The ratios of neutral-current candidates (short events) to charged-current candidates (long events), R_{meas} , are 0.4198 ± 0.0008 in the neutrino beam and 0.4215 ± 0.0017 in the anti-neutrino beam.

R_{meas} is related to the ratios of cross-sections and $\sin^2 \theta_W$ using a detailed detector and cross-section Monte Carlo simulation with the tuned flux (Figure 1) as input. This Monte Carlo must predict the substantial cross-talk between the samples. In the neutral-current sample, the backgrounds in the neutrino and anti-neutrino beam from $\nu_\mu/\bar{\nu}_\mu$ charged-current events are 19.3% and 7.4%, and the backgrounds from $\nu_e/\bar{\nu}_e$ charged-currents are 5.3% and 5.8%. The charged-current sample has only a 0.3% background from neutral-current events for each beam.

The important details of the detector for this analysis are the calorimeter response to muons, the measurement of the neutrino interaction vertex, and the range of hadronic showers in the calorimeter. The efficiency, noise and active areas of the scintillation counters are all measured using neutrino data or muons from the testbeam. Longitudinal and transverse vertex resolutions and biases are studied using a GEANT-based detector Monte Carlo. The longitudi-

dinal bias arises from splashback in the hadronic interaction and is measured from the data using track-based vertices in events with two energetic final state muons. Hadronic shower length in the calorimeter is measured using hadrons from the testbeam. To study possible effects from the difference in strange-quark content between neutrino-induced and π^- -induced showers, hadronic showers from K^- s are used as a cross-check. No significant differences are observed. Measured detector parameters are varied within their uncertainties in the Monte Carlo to study systematic errors associated with this simulation.

The cross-section model is of paramount importance to this analysis. Neutrino-quark deep-inelastic scattering processes are simulated using a leading-order cross-section model. Neutrino-electron scattering and quasi-elastic scattering are also included. Leading-order parton momentum distributions come from a modified Buras-Gaemers parameterization[8] of structure function data from the CCFR experiment[9] which used the same target-calorimeter and cross-section model as NuTeV. The parton distributions are modified to produce u and d valence and sea quark asymmetries consistent with muon scattering[10] and Drell-Yan[11] data. The shape and magnitude of the strange sea come from an analysis of events in CCFR with two oppositely charged muons (e.g., $\nu q \rightarrow \mu^- c$, $c \rightarrow \mu^+ X$)[12]. Mass suppression from heavy quark production is generated in a slow-rescaling model whose parameters are measured from the same dimuon data. The charm sea is taken from the CTEQ4L parton distribution functions[13]. The magnitude of the charm sea is assigned a 100% uncertainty and the slow-rescaling mass for $(\nu/\bar{\nu})c \rightarrow (\nu/\bar{\nu})c$ is varied from m_c to $2m_c$. Our parameterization of $R_{\text{long}} = \sigma_L/\sigma_T$ is based on QCD predictions and data[14] and is varied by 15% of itself in order to estimate uncertainties. Electroweak and pure QED radiative corrections to the scattering cross-sections are applied using computer code supplied by Bardin[15], and uncertainties are estimated by varying parameters of these corrections. Possible higher-twist corrections are considered with a 100% uncertainty using a VMD-based model which is constrained by lepto-production data[16].

The key test of the Monte Carlo is its ability to pre-

SOURCE OF UNCERTAINTY	$\delta \sin^2 \theta_W$
<i>Statistics:</i>	
Data	0.00188
Monte Carlo	0.00028
TOTAL STATISTICS	0.00190
$\nu_e/\bar{\nu}_e$	0.00045
Energy Measurement	0.00051
Event Length	0.00036
TOTAL EXP. SYST.	0.00078
Radiative Corrections	0.00051
Strange/Charm Sea	0.00036
Charm Mass	0.00009
$u/d, \bar{u}/\bar{d}$	0.00027
Longitudinal Structure Function	0.00004
Higher Twist	0.00011
TOTAL PHYSICS MODEL	0.00070
TOTAL UNCERTAINTY	0.0022

Table 1: Uncertainties in $\sin^2 \theta_W$

dict the length distribution of events in the detector. Figure 2 shows good agreement between the data and Monte Carlo within the systematic uncertainties.

To compute $\sin^2 \theta_W$, a linear combination of R_{meas}^ν and $R_{\text{meas}}^{\bar{\nu}}$ was formed,

$$R_{\text{meas}}^- \equiv R_{\text{meas}}^\nu - \alpha R_{\text{meas}}^{\bar{\nu}}, \quad (5)$$

where α is calculated using the Monte Carlo such that R_{meas}^- is insensitive to small changes in the slow-rescaling parameters for charm production. $\alpha = 0.5136$ for this measurement. This technique is similar to an explicit calculation of R^- , but here the background subtractions, the cross-section corrections to Eqn. 4, and the dependence on $\sin^2 \theta_W$ are calculated by Monte Carlo. This approach explicitly minimizes uncertainties related to the suppression of charm production, largely eliminates uncertainties related to scattering from sea quarks, and reduces many of the detector uncertainties common to both the ν and $\bar{\nu}$ samples. Uncertainties in this measurement of $\sin^2 \theta_W$ are shown in Table 1.

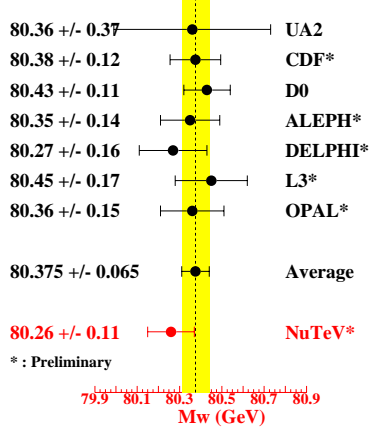


Figure 3: Current direct M_W measurements compared with this result

The preliminary result from the NuTeV data is *

$$\sin^2 \theta_W^{(\text{on-shell})} = 0.2253 \pm 0.0019(\text{stat}) \pm 0.0010(\text{syst}) \quad (6)$$

$$-0.00142 \times \left(\frac{M_{\text{top}}^2 - (175 \text{ GeV})^2}{(100 \text{ GeV})^2} \right) + 0.00048 \times \log_e \left(\frac{M_{\text{Higgs}}}{150 \text{ GeV}} \right). \quad (7)$$

The small residual dependence of our result on M_{top} and M_{Higgs} comes from the leading terms in the electroweak radiative corrections[15]. Since $\sin^2 \theta_W^{(\text{on-shell})} \equiv 1 - M_W^2/M_Z^2$, this result is equivalent to

$$M_W = 80.26 \pm 0.10(\text{stat}) \pm 0.05(\text{syst}) \quad (8)$$

*The weak radiative correction applied to extract $\sin^2 \theta_W^{\text{on-shell}}$ from the measured quantities has changed since the presentation at Moriond due to an error in the implementation of the Bardin code for radiative corrections. Two other small experimental corrections, for muon energy deposition and for charm semi-leptonic decays, were improved as well. The net shift in the result, 0.0054, is dominated by the fix in the implementation of the radiative corrections.

$$+0.073 \times \left(\frac{M_{\text{top}}^2 - (175 \text{ GeV})^2}{(100 \text{ GeV})^2} \right) - 0.025 \times \log_e \left(\frac{M_{\text{Higgs}}}{150 \text{ GeV}} \right). \quad (9)$$

A comparison of this result with direct measurements of M_W is shown in Figure 3.

It is possible to extract the NuTeV result in a model-independent framework, where the result is expressed in terms of combinations of the left and right-handed quark couplings. The linearized constraint (expanded around one-loop couplings at an average $\log_{10} \left(\frac{-q^2}{1 \text{ GeV}^2} \right) \approx 1$ for NuTeV's central value of $\sin^2 \theta_W$) is

$$\begin{aligned} 0.4530 - \sin^2 \theta_W &= 0.2277 \pm 0.0022 \\ &= 0.8587u_L^2 + 0.8828d_L^2 \\ &\quad - 1.1657u_R^2 - 1.2288d_R^2. \end{aligned} \quad (10)$$

Note the similarity of this result to $1/2 - \sin^2 \theta_W = g_L^2 - g_R^2$, the definition of the Paschos-Wolfenstein R^- in Eqn. 4.

(It is also possible to combine the NuTeV result with data from NuTeV's predecessor, the CCFR experiment. Adding the CCFR data[4] in the R_{meas}^- -based method described above, we obtain a slight improvement in precision, $\sin^2 \theta_W = 0.2255 \pm 0.0018(\text{stat}) \pm 0.0010(\text{syst})$.)

4 Conclusions

The NuTeV experiment has completed its data-taking and has extracted a preliminary result for $\sin^2 \theta_W^{(\text{on-shell})}$, which is equivalent to M_W in the Standard Model. The precision of this result is approximately a factor of two improvement over previous measurements in νN scattering because of the reduced systematics associated with measuring the Paschos-Wolfenstein ratio, R^- . This result is consistent with the average of direct M_W data.

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